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Survivability, Structures, and Materials Directorate

Technical Report

Failure Analysis of an Inland Waterway Oil Bunker Barge

by

Paul E. Hess III

John C. Adamchak

Jaye Falls

Failure Analysis of an Inland Waterway Oil Bunker Barge

NSWCCD-TR-65–97/01

DEPARTMENT OF THE NAVY

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1. Reference (a) directed the Naval Surface Warfare Center, Carderock Division (NSWCCD) to conduct a finite element analysis to help determine the cause of two similar marine casualties of the tank barges *Buffalo 286* and *Buffalo 292*. Enclosure (1) describes a study to numerically predict the structural load response at the time of failure. The ultimate strength of the barge under vertical hull girder bending was also calculated, and commentaries on the possible reasons for the structural failure are presented.

2. Comments or questions may be referred to the principal investigator, Mr. Paul E. Hess III, Code 654; telephone (301) 227-4118; e-mail, hess@oasys.dt.navy.mil.

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A barge which was designed in accordance with American Bureau of Shipping rules for inland waterways barges less than 300 feet long underwent ultimate hull girder collapse while underway in the Galveston Bay, near Houston, Texas. Two numerical analyses were conducted to determine the ultimate strength and the stress levels under operational loading. Commentary on the possible reasons for the failure are presented.

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ABSTRACT

A barge which was designed in accordance with American Bureau of Shipping rules for inland waterway barges less than 300 feet long, underwent ultimate, hull girder collapse while underway in the Galveston Bay, near Houston, Texas. Two numerical analyses were conducted to determine the ultimate strength and the stress levels under operational loading. Commentary on the possible reasons for the failure are presented.

ADMINISTRATIVE INFORMATION

The work described herein was performed by the Structures and Composites Department, Code 65, of the Survivability, Structures and Materials Directorate. It was funded by the Marine Safety Center of the United States Coast Guard as part of a casualty investigation.

1.0 INTRODUCTION

1.1 Background

An oil bunker barge known as the *Buffalo 286*, used in the Galveston Bay near Houston, Texas experienced hull girder collapse while being pushed in a seaway. A video of the barge and eyewitness accounts show that the barge suffered compressive, buckling failure in the strength deck, leading to overall, hull girder collapse.

The barge was designed in accordance with American Bureau of Shipping rules which were developed for use in the design of barges used on bodies of comparatively smooth water. These rules address barges of any length, but specify limits on Length to Depth and Breadth to Depth ratios. Several years ago, the Coast Guard extended the application of these inland rules to barges operating on lake, bay and sound routes, such as Galveston Bay. Approximately 1000 of these oil barges are in service. The collapse in

Galveston Bay initiated a casualty investigation by the Eighth Coast Guard District. The Coast Guard is addressing the causes of the collapse and will recommend revisions to the rules of operation and construction to prevent such incidents in the future. The objectives of this study were to assess the global structural behavior under operational loads and to identify and investigate possible causes for the failure. Recommendations for future work are contained in the conclusions.

The barge used in this study has dimensions shown in Table 1.1.1. Except for some rake in the first 40 feet, the barge is prismatic with a rectangular cross-section. As material strength test results were not available at the time of this study, a material yield strength of 32 ksi is used in this study (Billingsley, 1984).

Table 1.1.1. Barge Dimensions.

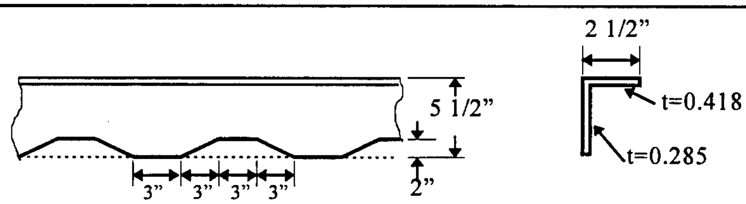
Length	290 ft.
Breadth	54 ft.
Depth	12 ft.
Lightship Displacement	527.3 LTons
Material Yield Strength	32 ksi

The interior of the barge is partitioned by a longitudinal bulkhead on the centerline and seven transverse bulkheads. Compartments 2 through 6 are used for tankage. Boundaries and designations are outlined in Table 1.1.2.

The longitudinal strength of the barge relies heavily on angle stiffeners cut from channel beams (See Figure 1.1.1). The stiffeners have webs serrated at the toe, and only contact the plating for three inches out of twelve. This results in intermittent welds to be required and nine inch unsupported plating spans in the longitudinal direction. These unsupported spans are causes for concern and are discussed further in Section 4 and the Appendix.

Table 1.1.2. Barge Compartmentation Boundaries.

Compartment	Tank	Begin Frame (at Transverse Bulkhead)	Begin Frame Distance from FP	End Frame (at Transverse Bulkhead)	End Frame Distance from FP
1	-	0	0	13	24' 10"
2	1	13	24' 10"	19	73' 4"
3	2	19	73' 4"	25	121' 10"
4	3	25	121' 10"	31	170' 4"
5	4	31	170' 4"	37	218' 10"
6	5	37	218' 10"	43	267' 4"
7	-	43	267' 4"	46	285'
8	-	46	285'	47	290'



Deck Stiffener: 5 1/2x2 1/2x5/16 S.S.
(cut from 9" C15#)

Figure 1.1.1. Deck Longitudinal (Serrated) Stiffener Dimensions.

1.2 Methodology

Analyses of the structural response of the barge were conducted using numerical modeling. MAESTRO was used for predicting structural response under operational loads and ULTSTR was used for predicting the ultimate hull girder strength.

The stress levels generated due to operation loading were quantified by analyzing a MAESTRO model of the barge. MAESTRO is a finite element based computer program which addresses the global loading condition of a ship under static seaway loading, accounting for structural, cargo, and buoyancy forces (*MAESTRO Users Manual*, v.7.0, 1995). The structure is analyzed using a coarse-mesh finite element analysis, which calculates stresses and displacements for the entire vessel. These stresses are applied to a set of limit state equations allowing the investigator to assess the adequacy of the structure. The results are quantified and reported as a set of Adequacy Parameters. The limit states contained in MAESTRO are discussed in Volume 3 of the MAESTRO Manuals (*MAESTRO Users Manual*, v.7.0, 1995) and are explained in depth in Hughes (1988). The Adequacy Parameters are a function of the ratio of various load effects and their associated limiting resistance values, this being known as the "strength ratio". Failure is defined as the strength ratio value being greater than unity. As a means of normalizing this ratio for the optimization routines in MAESTRO, the adequacy parameter function has been defined:

$$\textit{Adequacy Parameter} = \frac{(\,1\ -\ \textit{Strength Ratio}\,)}{(\,1\ +\ \textit{Strength Ratio}\,)}$$

The range of values of adequacy parameters is negative one to positive one. On this scale, values greater than zero satisfy design criteria. Values between -0.01 and 0.01 are considered within a transitional region which is not definitive of failure or success. It is important to note the nonlinearity of the scale. An adequacy parameter value of -0.10 corresponds to a strength 22% under the required design limit strength. An adequacy parameter value of +0.10 corresponds to a strength 18% over the required design limit strength.

HECSALV is a computer code which analyzes the behavior of surface ships under varying loading conditions and predicts the resulting displacement, vertical bending moment, hull girder stresses, draft, trim and heel. It is intended to assist in salvage efforts for vessels which have undergone structural damage and/or compartmental flooding (*HECSALV*, v.5.21, 1996). HECSALV was used to duplicate of the loadcase which contributed to the Galveston Bay barge collapse as well as three other potential loadings. Structural responses due to lateral bending and torsion were not investigated as the observed failure mechanism appears to be a result of primary bending in the vertical plane.

The ULTSTR (Ultimate Strength) computer program was originally developed about fifteen years ago (Adamchak, 1982). At that time, its intended use was for the estimation of the hull girder ultimate or peak bending moment capacity in longitudinal bending in the preliminary structural design stage. For about ten years, ULTSTR saw only limited application, most frequently in a research rather than a design environment. About five years ago, interest in hull girder ultimate strength dramatically increased, and the program experienced widespread and frequent application. Because of this increased interest, ULTSTR has been extensively modified and enhanced during this time period, a process which is continuing at the present time.

Because ULTSTR is intended for early stage design, much of its foundation is based on basic strength of materials theory and empirically developed formulations. Although it is not a finite element based program, ULTSTR works by subdividing the hull girder cross section into a number of panel (stiffened or unstiffened) or hard corner elements and then sequentially imposes a series of small curvature increments on the total hull cross section. The curvature increments produce corresponding strain increments in the various elements and these, in turn, lead to increments of stress which when integrated over the total cross section, result in force and moment values. The location of the correct neutral axis for each curvature increment is based on the fact that the hull is undergoing bending alone, and therefore the net axial force on the cross section must be zero. When carried out over a "large" number of curvature increments, the desired moment-curvature relationship is developed. This relationship is generally characterized by a rapid rise to the peak or ultimate bending moment value (this usually being the quantity the user is seeking), followed by a drop from this value which may either be precipitous or gradual depending on the characteristics of the hull girder cross section. The theory and operation of the ULTSTR program is described in Adamchak (1996), which is a very recent revision of the original users manual.

Several recent tests on "hybrid-scaled" hull cross section models have given a degree of credibility to ULTSTR which would not have been possible five or more years ago. Hybrid-scaled means that the detailed scantlings and the principal dimensions have different scale factors. In addition, ULTSTR played a key role in the recent live-fire tests on the Navy's LPD-1, this ship serving as a surrogate for the new LPD-17 class currently in design. ULTSTR is also directly supporting the design of the LPD-17, the first time an overall hull girder ultimate strength requirement has been explicitly imposed on a Navy hull.

One of the more significant enhancements recently made to ULTSTR was the addition of several optional "plate strength" models. For unstiffened plating the plate strength model defines the in-plane compressive strength, whereas, for stiffened panels, the plate strength model is primarily used to define the effective width and breadth of the plating when used as the plate flange in a plate-beam cross section. The additional models were incorporated as a means of implicitly addressing the influence of varying amounts of plating distortion on the strength of the hull girder cross section. Because plating behavior under in-plane compression is strongly influenced by both distortion amplitude and modal content, ULTSTR, at present, is not capable of explicitly relating a plate strength model to a specified amplitude of plate distortion. Plate strength models which are currently built into ULTSTR are intended to simulate the behavior of plating having distortion levels corresponding to one of four levels of severity: 1.) Plating nearly perfectly flat; 2.) Plating with moderate levels of distortion; 3.) Plating with moderate-severe levels of distortion, and 4.) Plating with severe levels of distortion. The moderate-severe distortion level is the default option in ULTSTR. This is the strength model that was built into the original version of the program.

1.3 Measured Stiffener Distortions

Investigators from the United States Coast Guard, Marine Safety Center measured the deck panel stiffener distortions in compartments 2, 3, and 4 (tanks 1, 2, and 3) of an intact, sister barge to discern whether distortion may have weakened the structure and predisposed it to fail. The distortion was measured along the strong axis of the stiffener, reflecting the eccentricity of the stiffened panel.

Measurements were taken in compartments 2 and 3 (tanks 1 and 2) to assess the longitudinal distribution of distortion. The sample sizes were rather small, with four samples from tank 1 and twelve from tank 2. The statistics are somewhat similar to those for tank 3 and are shown in Table 1.3.1.

Table 1.3.1. Stiffener Strong Axis Distortion Statistics (97 inch span) for Tanks 1 and 2.

Statistic	Tank 1 (32nd's in.)	Tank 2 (32nd's in.)
Mean	2.125	3.063
Standard Deviation	1.315	2.031
Median	1.75	2.125
Minimum	1	0.75
Maximum	4	7.5
Sample Size	4	12

The statistics of the distortions for compartment 4 (tank 3) are shown in Table 1.3.2, and the distribution is shown in Figure 1.3.1. This compartment represents the approximate conditions of the damaged region of the barge which collapsed prior to failure. Another way of viewing the statistics is considering the mean distortion as the span divided by 1036 and the standard deviation as the span divided by 1577. The histogram in Figure 1.3.1 shows that there is roughly a 5% chance that the distortion will approach 1/4 inch.

Table 1.3.2. Stiffener Strong Axis Distortion Statistics (97 inch Span) for Tank 3.

Statistic	(32nd's of an inch)
Mean	2.781
Standard Deviation	1.826
Median	2.3
Mode	1.5
Minimum	0.0
Maximum	7.8
Sample Size	84

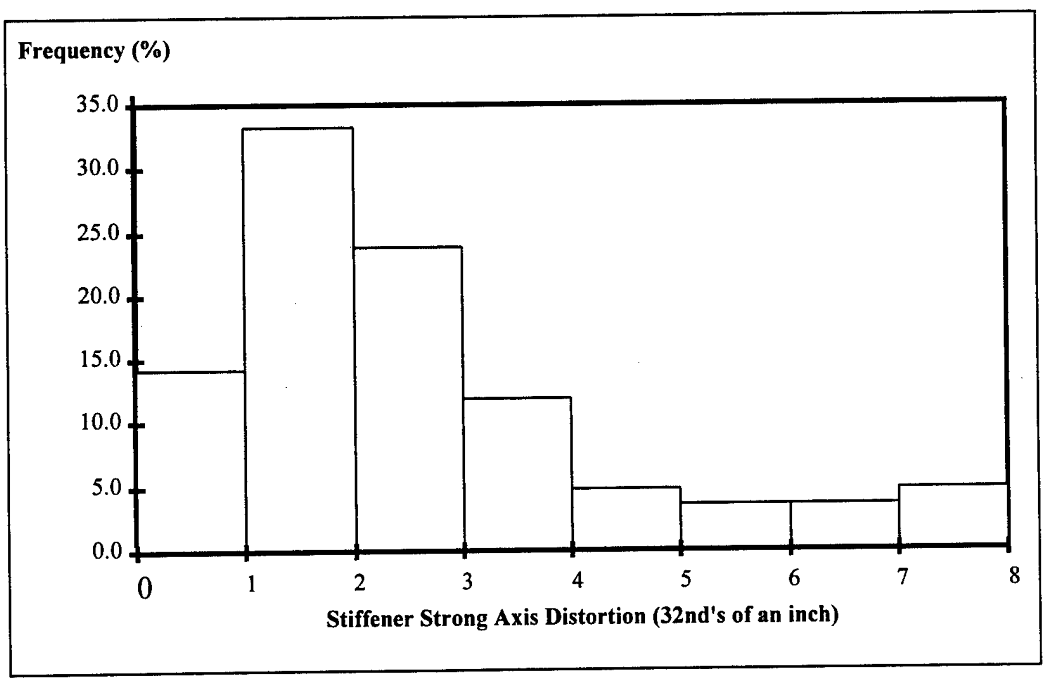


Figure 1.3.1. Stiffener Strong Axis Distortion Distribution (97 inch Span).

2.0 STRUCTURAL RESPONSE DUE TO OPERATIONAL LOADING

2.1 MAESTRO Model Generation

A MAESTRO model was generated of the barge from frame 13 (28 feet aft of the Forward Perpendicular, or FP) to the transom. Simplifications of the structure were necessary to create the model. The serration's in the longitudinal stiffeners were beyond the level of detail of the analysis, and their effects were not included. As discussed in more detail later, the 9-inch unsupported spans of plating between stiffener attachment welds are believed to significantly decrease panel load-carrying capacity. Consequently, the calculated strengths from the MAESTRO model are probably overly optimistic.

The transverse frames (channel sections) used in construction were welded to the flanges of the longitudinal stiffeners. A simplification of this detail was used with the equivalent stiffness of the channel being input and the contribution of the plating considered negligible. The buck frames and superelements were modeled to maintain the transverse stiffness contribution, but not in such a way as to allow an analysis of their stress levels.

2.2 Loadcases Applied to the MAESTRO Model and Resulting Stresses

Four loading conditions were investigated and are outlined below. The first three loadcases involve a combination of structural weight, internal cargo forces and buoyancy forces. The cargo loads are modeled as applied pressures inside the holds of the barge. The fourth loadcase considers pure bending only. The maximum vertical bending moments and resulting stresses are listed in Table 2.2.1. All loadcases result in a sagging bending moment (deck in compression).

The first loadcase models the barge loading at the time of failure. The liquid cargo was loaded into tanks 2,3,4 and 5 with quantities shown in Table 2.2.2. The vessel was balanced in a stillwater condition.

Table 2.2.1. Vertical Bending Moments and Stresses per Loadcase.

Loadcase	Max. Vertical Bending Moment (ft-LTons)	Max. Vertical Bending Moment (in-lb.)	Longitudinal Stress (σ_X) (ksi)	Transverse Stress (σ_Y) (ksi)
1	24981.1	$-6.71*10^8$	-16.59	-0.98
2	24864.2	$-6.68*10^8$	-16.61	-1.11
3	31303.0	$-8.41*10^8$	-20.63	-2.29
4	31783.5	$-8.54*10^8$	-21.1	-1.1

Note: Bending moments are in sag, and reported stresses are compressive.

Table 2.2.2. Tankage Liquid Cargo Depth for Loadcases 1 and 2.

Tank	Liquid Free Surface Height Above Baseline (ft)
2	10.94
3	10.88
4	7.4
5	8.24

The second loadcase carried the cargo loading outlined in Table 2.2.2, but the vessel was statically balanced on a wave profile. The wave has a length of 150 ft and a height of 5 ft. The trough of the wave was located at midships to enhance the sagging moment.

The third loadcase is based on the cargo distribution leading to the maximum vertical bending moment at midships. Tanks 3 and 4 were completely filled, simulating a liquid depth of 12 ft, with all other tanks empty. The barge was analyzed under stillwater conditions.

The fourth loadcase used the bending moment predicted from ULTSTR for ultimate collapse. No internal cargo, external buoyancy forces, or structural weight were included. The structure was placed in a state of pure bending with moments applied at the ends of the MAESTRO model.

The stress levels for normal full cargo loads (loadcases 1 and 2) are quite high and result in small margins of safety relative to the stress levels occurring at the point of ultimate collapse. The possibility of an intermediate point in the loading sequence similar to that represented by loadcase 3 suggests that without general guidelines on loading there is a strong probability of a barge experiencing failure at the dockside during the loading process.

The transverse stresses occur in the panels with the highest longitudinal stresses shown in Table 2.2.1, and are not meant to be the maximum's encountered. They are the result of the sagging bending moment tending to push the top (compressive flange) corners of the box section inward. The opposite effect occurs on the bottom (tensile flange) with the corners being spread apart, causing the resulting panel transverse stresses to be tensile. The magnitudes are rather inconsequential relative to the effects of the longitudinal stresses which are of primary concern.

2.3 Barge Structural Adequacy

Design of a structure usually allows for a margin ("Safety Factor" or "Factor of Safety") between potential loadings and the structural resistance. This conservatism provides for a level of safety, and acknowledges uncertainty in the design methods. Should there be an inadequate margin, there is a possibility that the predicted loads may exceed the predicted structural strength (limit states) resulting in a structural failure.

The structural response of the barge for the load at failure (loadcases 1 and 2) showed behavior which allows for a minimal safety factor. For the remaining loadcases (3 and 4), the deck structure is judged by MAESTRO to be quite inadequate, with safety factors less than one. These results are consistent with, but appear slightly more conservative than, the ULTSTR results discussed later in this report. The analysis shows that the stiffened panels in the deck are likely to collapse due to buckling of the "stiffener columns", and the plating between stiffeners may experience local buckling. The resulting values of the adequacy parameters and the ratio between the strength and the load are shown in Table 2.3.1.

Table 2.3.1. Limit State Adequacy for Each Loadcase.

Governing Failure Mode for Deck	Loadcase	Adequacy Parameter	Safety Factor
Stiffener Column Buckling	1	0.04	1.08
	2	0.04	1.08
	3	-0.08	0.85
	4	-0.15	0.74
Local Buckling of Plating	1	0.03	1.06
	2	0.02	1.04
	3	-0.11	0.80
	4	-0.14	0.75

Note: Safety Factor shown is ratio of the strength to the load. (This is the inverse of the strength ratio discussed in Section 1.2)

The stiffener and plate failure modes are discussed in depth in Hughes (1988). As the Adequacy Parameters are practically identical for the plate and stiffened panel failure modes for each loadcase, the importance of one component versus another (stiffener size vs. plate thickness) is hard to discern. Assuming the stiffener serrations and discontinuous welds have no effect on the strength (not a trivial assumption), the stiffened panel structural system is apparently designed such that there is no effective margin of safety for the encountered loading. Traditionally, in the design of longitudinally stiffened panels, the plating is allowed or considered to be weaker than the stiffener-plate columns when it comes to evaluating the ultimate strength of the panel. The reserve strength beyond the onset of failure tends to be greater in the stiffener column than the unstiffened plating. As the plating's effectiveness in carrying the load decreases the plating sheds its load to the stiffener columns which become instrumental in carrying the compressive loading up to the point of ultimate collapse. Increasing the plating thickness may not necessarily help the situation, unless this improvement markedly increases the strength of the stiffener column. It is important to emphasize the underlying assumptions used in the traditional stiffened panel strength, design and analysis methods as used in this study. These methods are predicated on the use of continuous welds being used to attach the stiffeners to the plating. For further exploration of the impact of the discontinuous welds and the stiffener serrations on the ultimate strength see Section 4.2 and the Appendix.

3.0 ULTIMATE STRENGTH ANALYSIS

In applying ULTSTR to the *Buffalo 286* barge design, the barge cross section was subdivided into nodes and elements as illustrated on Figure 3.1. Although the full breadth of the barge was modeled, only half of the cross section is shown on the figure since the "mirror image" option was used in the modeling. As the name implies, this option allows the input data volume to be substantially reduced for the symmetric sections of the structure by having the program interpret any node (or element) number skipped as being the mirror image of the immediately preceding node (or element). In the half model there are 54 nodes, 41 panel elements and 18 hard corner elements.

The current version of ULTSTR has many available options which are described in some detail in the user's manual[4]. For these initial runs on the *Buffalo 286* barge all these options were assigned their default values with the exception of the plate strength

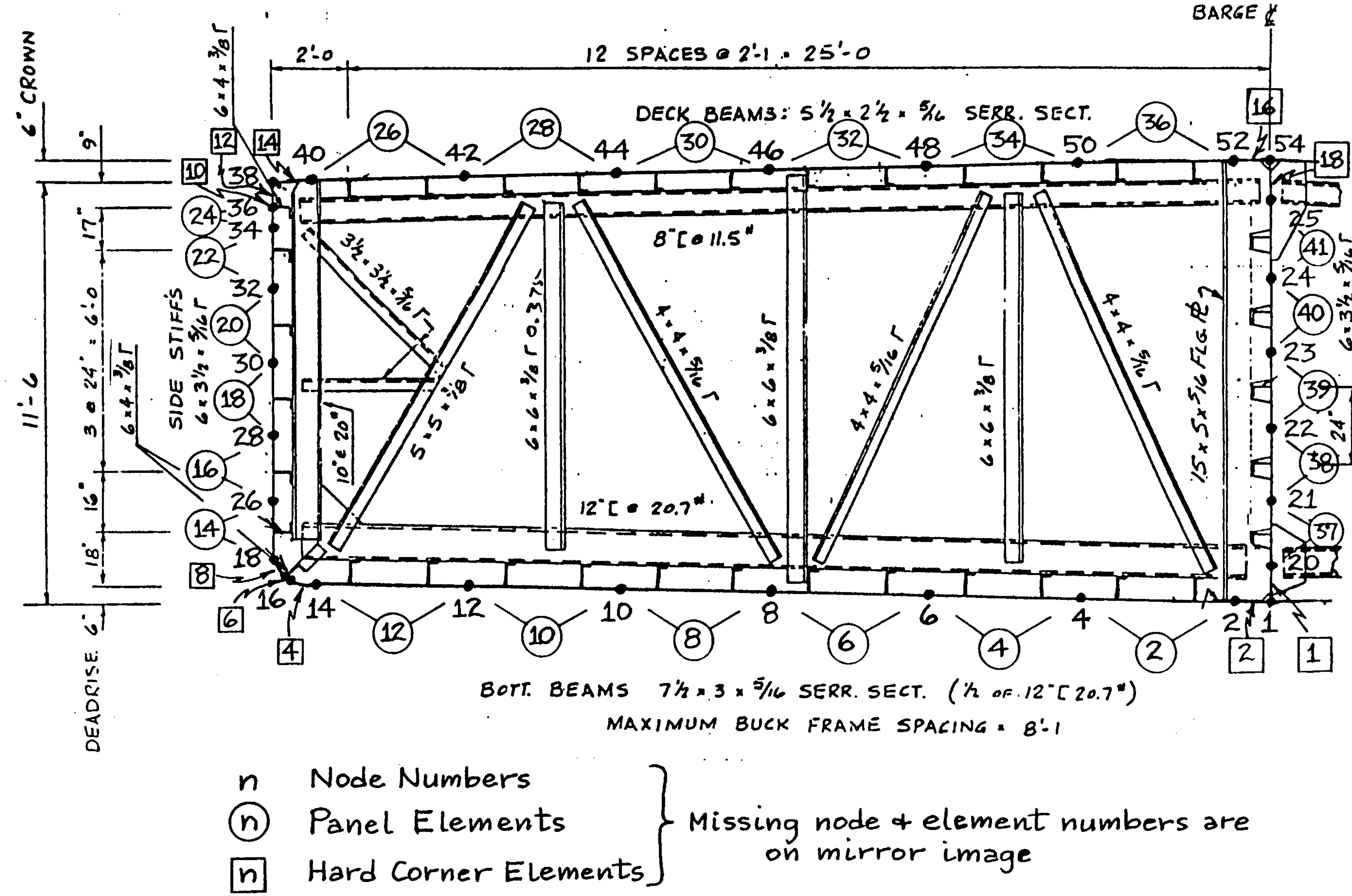


Figure 3.1. ULTSTR Half-Model of the *Buffalo 286.*

model. Four runs were made, one run corresponding to each of the four plating distortion severity levels. These results are presented in Table 3.1, where the peak or ultimate bending moment is seen to vary between a high of -9.83×10^8 in-lb (the negative sign indicates a sagging moment) for plating nearly perfectly flat and a low of -8.12×10^8 in-lb for severely distorted plating. (All runs were made with a material yield stress of 32 ksi.) If these moment values are divided by the hull girder cross section's fully effective section modulus (computed from a moment of inertia of 3.294×10^6 in^4 with a neutral axis location 63.2 in ABL), these collapse values can be expressed in terms of a mean stress, varying from 25.9 ksi to 21.4 ksi.

Table 3.1. Ultimate Bending Moments and Associated Stresses from ULTSTR Analysis for Different Levels of Plate Distortion.

Plate Distortion Severity	Collapse Moment (in-lb)	Effective Mean Stress (ksi)
Nearly Flat	$-9.83*10^8$	-25.9
Moderate	$-9.16*10^8$	-24.2
Moderate-Severe	$-8.64*10^8$	-22.8
Severe	$-8.12*10^8$	-21.4

Note: Bending moments are in sag, and reported stresses are compressive.

The plate strength models only address the distortion levels in the plating, if lateral (strong axis) stiffener distortion is known or suspected, such values can be explicitly defined in the program. Not specifying a value of stiffener lateral distortion does not imply there is none; rather it suggests that the distortion levels present are nominal and are handled by the empirical nature of the failure mode algorithms. In fact, for very small levels of initial stiffener distortion, the failure mode theories that do not treat distortion explicitly may give lower values of plate-stiffener compressive strength.

However, as the stiffener distortion values increase with increasing load, a threshold level of distortion will eventually be reached, beyond which the explicit treatment will govern, i.e., will give lower plate-stiffener compressive strengths.

For the *Buffalo 286* barge model, values of stiffener lateral distortion ranging from 0.25 inch (0.26 % of the span) to 1.50 inches (1.55 %) were applied in ¼-inch increments and the results tabulated in Table 3.2. These distortion values were applied to all the panel elements of the upper deck and the uppermost panel element on both the port and starboard side shell. The default plate strength model (moderate-severe distortion) was used for all these analyses. As the table indicates, the relative strength levels (as compared to the case when no distortion level is specified) ranged from 96.1% for a distortion level of 0.25 inch to 69.1% for the largest value of 1.50 inches.

Table 3.2. Ultimate Bending Moments and Strength Reductions from ULTSTR Analysis for Different Levels of Stiffener Distortion.

Stiffener Distortion (in)	Collapse Moment (in-lb)	Relative Strength (%)
0.25	$-8.30*10^8$	96.1
0.50	$-7.72*10^8$	89.4
0.75	$-7.20*10^8$	83.3
1.00	$-6.76*10^8$	78.2
1.25	$-6.36*10^8$	73.6
1.50	$-5.97*10^8$	69.1

Note: Bending moments are in sag; stiffener length is 97 inches.

From the distribution of measured distortion values in Figure 1.3.1, it can be seen that there is a probability of around 5% of achieving a distortion level of approximately

0.25 inch for each of the panels in the deck, with a greater likelihood (~17%) of a distortion level of 0.125 inch or greater. Distortion may allow the strength to be degraded as seen in Table 3.2, but with the caveats as discussed below.

To have large distortion levels present in all the elements of the upper deck (as shown in Table 3.2) probably represents a rather unlikely scenario, unless such levels were always present (most likely from initial fabrication) or resulted over a relatively long period of time from several instances of overloading the hull, so-called progressive damage. Large lateral deformations of stiffeners (denting) due to collisions, accidents (dropped cargo, for example) would seem more likely to be a localized phenomenon and the resulting loss of ultimate strength more moderate. For example, if only stiffened panel elements 35 & 36 (representing a total of 4 stiffeners) were "dented" to a level of 1.5 inches, the peak moment degrades to 8.62×10^8 in-lb, a loss in strength of only about 0.3%.

Another explaination for the barge collapse was the possibility that the longitudinals in the side shell may have become detached from the web frames. This possible configuration was modeled in ULTSTR by changing the effective column length of the elements in the side shell from 97 inches (the web frame spacing) to a value of 180 inches. Effectively no change in collapse moment was noted. This appears to be due to the almost total dominance of the elements in the upper deck in defining the collapse moment of this structure. Having a very shallow hull form, the area of the side shell undergoing compression is a very small percentage of the total, and thus the influence of the side shell on the collapse moment is minimal. For frames detaching from the web frames to be significant it would appear that this would have to occur on either the upper deck (for sagging failure) or the bottom (for hogging).

The ULTSTR program assumes that stiffened panel failures occur in one of three possible interframe buckling modes, meaning that the web frames are strong enough to force the buckling pattern to have nodal lines at the web frame locations. Although there has been no visual (or other) evidence to suggest that this was not the case, a check was made to attempt to eliminate general instability (in which the web frames also buckle) as a potential failure mode. Adamchak (1975) describes an approximate method for quickly estimating the general instability failure loads of cross stiffened grillages using a discrete-beam energy approach. A computer program based on this method was used to evaluate the upper deck grillage structure of the *Buffalo 286* barge design. The design of the web frames with the numerous supporting members gives an unsupported span in the transverse direction comprising at most three longitudinal stiffeners or, being generous, a breadth of approximately 100 inches. Assuming the stiffness of the web frame is almost totally that of the 8-inch channel member, the general instability program was run for several possible values of mode number corresponding to the longitudinal direction. As expected, the minimum general instability failure load occurred for a mode number of 6, corresponding to interframe buckling. (The compartment has 5 web frames at a uniform spacing of 97 inches.) Interestingly enough, if the unsupported transverse breadth was increased by one longitudinal stiffener (to about 125 inches), the mode number corresponding to the minimum general instability load jumped to 3. This may be a little misleading, however, since simply supported boundary conditions were used for all these calculations and there is definitely a degree of conservatism in this assumption.

4.0 UNRESOLVED ISSUES

Even if one accepts the premise that there is an inadequate margin between the hull girder strength of the *Buffalo 286* barge design and the primary loading levels which are known occur, this in itself does not explain the hull failures that have occurred. Other possible contributors to these failures which need to be explored further are discussed below.

4.1 Tripping Instability of Angle Stiffeners

For a number of years there has been a debate within the structures community over the relative merits of tee versus angle stiffeners with regard to lateral-torsional (tripping) instability. One argument holds that, since angles are unsymmetrical in geometry and thus immediately start to deform out-of-plane when a compressive axial load is applied, they are inherently weaker in tripping than an equivalent tee stiffener. An opposing view suggests that when an angle undergoes tripping, it will bend about an axis inclined at some angle to its web, thus making the web as well as the flange effective in resisting tripping, resulting in a comparatively stronger cross section. Another view straddles both sides of this argument, suggesting that their relative merits are geometrically dependent, in some cases angles being stronger and in other cases weaker than their equivalent tee. Since all the longitudinal stiffeners in this design are angles, this issue is clearly relevant.

The U.S. Navy has never devoted much effort towards understanding the tripping behavior of angles, primarily because they generally do not use them. With increased emphasis being placed on reducing costs this situation may change and the Navy may be forced to confront this issue. Yet with many commercial and foreign ships using flat bar and bulb angle stiffeners (which without doubt are relatively weak in tripping) it is hard to imagine that the use of angles alone could explain the possible overprediction of the hull strength.

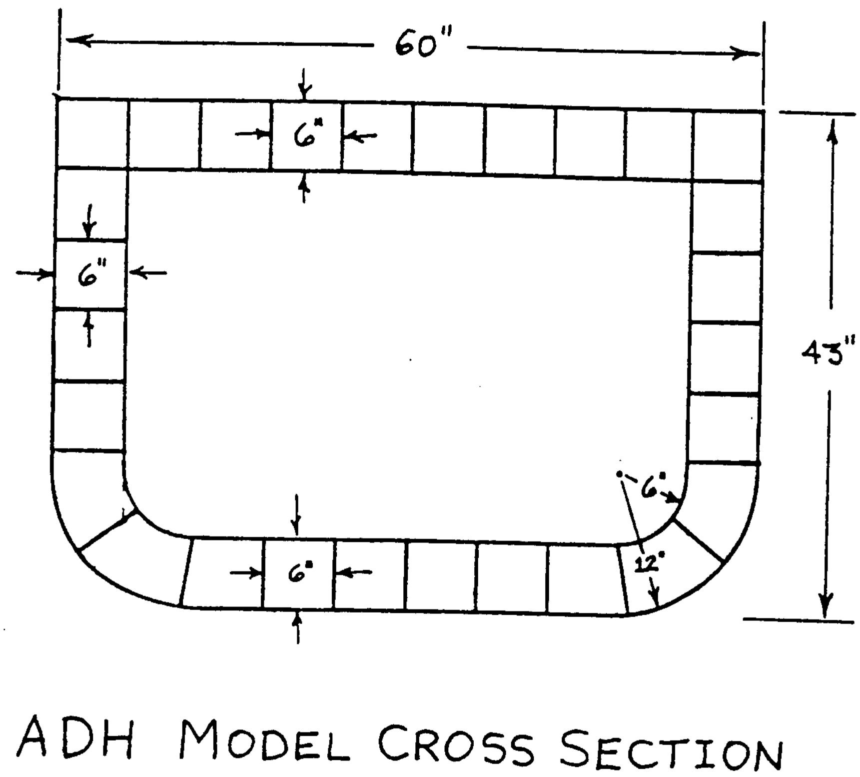
4.2 Intermittent Welding/Serrated Stiffeners

The use of intermittent welding combined in this case with serrated stiffeners is a clever cost saving technique, but one must wonder whether there are some undesired, currently unrecognized consequences of this practice.

A recent Navy program focusing on the Advanced Double Hull (ADH) concept resulted in what is now seen as a fortuitous oversight that is by coincidence extremely relevant to this topic. As part of this program, a hybrid-scaled 90 foot ADH model was tested in a quarry to investigate dynamic hull behavior under impulsive loading. The cross section of this model is shown on Figure 4.2.1. Through an oversight, this model was constructed including what will be called "weepholes" in the longitudinal girders in the lower portion of the hull. These openings are a standard feature in Navy hulls to allow drainage between compartments, as well as for other reasons. The geometry of these weepholes as placed in the ADH model is also shown in the Figure 4.2.1. Their presence might not have become an issue except for the fact that the weephole openings were made full-scale (a 3-inch diameter semicircle) whereas the plating was approximately 0.10 inch, about one-third to one-fifth scale, depending on the size of the reference hull. What resulted was that the span of the unsupported plating at the weephole location was three to five times the scale factor of the hull.

When this model was dynamically tested it became apparent that the model had failed prematurely and that the presence of the weepholes was probably the main contributor. At the time of the test, the degree to which the strength was degraded was unknown, but shortly thereafter a relatively undamaged section of the hull was statically tested and more recently an identical model with the same cross section without weepholes was also statically tested. On the basis of these tests it was estimated that the model containing the weepholes experienced a reduction in moment capacity of about 18-20%.

What makes this data particularly relevant becomes clear when the geometry of the plating and serrated stiffeners used in the upper deck is examined. For every 12 inches of length, 9 inches of plating is unsupported. This gives an unsupported span to thickness ratio of 28.8 for the upper deck. The ADH dynamic model with the 3 inch semicircle and 0.10 inch plating gives an equivalent value of 30. The similarities of the geometry's is remarkable. While this similarity does not guarantee that a loss in hull girder strength of the same percentage will occur in the barge hull, the circumstantial evidence is simply too strong to ignore. Clearly, the ramifications of using intermittently



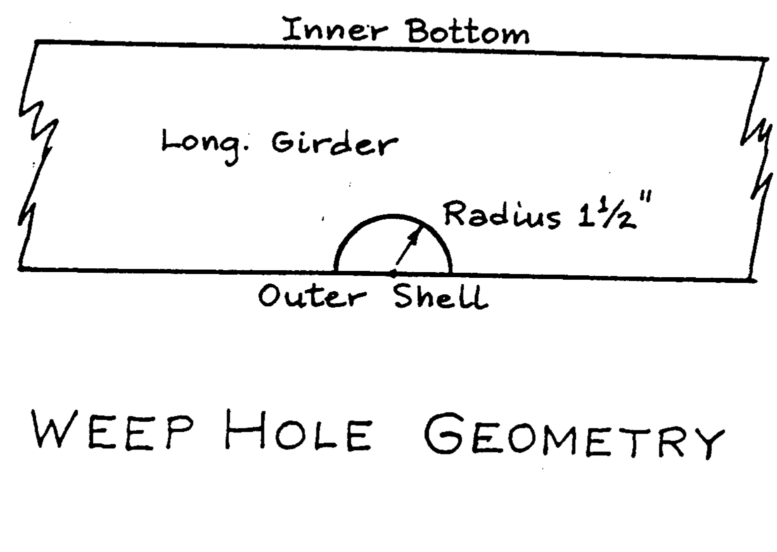


Figure 4.2.1. Advanced Double Hull Model Cross Section and Weephole Geometry.

welded, serrated stiffeners (or more generally, any construction technique which incorporates long lengths of unsupported plating) would have to be viewed as a prime candidate for explaining the seemingly premature barge failures.

A sufficiently rigorous look at the behavior of intermittently welded, serrated plate stiffener combinations is beyond the scope of this study. Because of the nature of the complex interactions involved, nonlinear finite element analysis is probably the only practical approach at this time which can address this problem. Particular attention needs to be devoted to developing models which can describe the behavior of the unsupported spans of plating between the stiffener welds. This includes taking into account potential distortion patterns in these segments of plating, whether due to initial fabrication or in-service effects. A quick, preliminary (and undocumented) study of the problems associated with the weepholes on the ADH model using the ABAQUS finite element program gave encouraging results which suggest that a similar approach applied to the serrated stiffener configuration would probably be successful.

4.3 Progressive Damage

Since many barges have been in service for relatively long periods of time, it is logical to ask why these failures haven't occurred until recently. Some research that the Navy has only recently begun may shed some light on this issue.

In some hybrid-scaled hull girder model tests performed recently, the results of loading, reverse loading and repeating cycles of loading have been examined. What has been learned is that when a hull girder is loaded in bending well past its elastic limit, its strength in that direction of loading (hogging or sagging) is permanently degraded. Even after the hull has been loaded in the reverse direction and the visible damage appears to have been "pulled" or "straightened" out, the effects of that damage are never completely erased. Consequently, when the loading returns to its previous direction the hull capacity has now been permanently reduced. This change in the strength due to inelastic behavior is considered progressive damage and should not be confused with what is commonly referred to as fatigue.

A logical consequence of this is that as a vessel ages and undergoes many loading and reloading cycles its longitudinal bending moment capacities in hogging and sagging will probably be reduced from its "as-built" values, particularly if it is subjected to occasional overloading. This is probably more likely to occur if the vessel is routinely operated at load levels too close to its strength limits. The *Buffalo 286* barge seems to fall into this category.

Since the type of failure associated with the intermittently welded/serrated stiffener configuration would appear to be very sensitive to any plating out-of-flatness, failure precipitated in this manner might also be particularly susceptible to progressive damage. Ship plating, when welded, is seldom flat and the continuous flexing of the plating due to repeating and reversing loading cycles over a period of many years of service could be expected to lead to a steady, if very gradual, increase in the distortion levels in the plating. Particularly damaging would be distortions occurring in those sections of the plating in close proximity to the unsupported spans of plating in way of stiffener distortions. Ironically, because of the lack of support, these areas might well be the areas most affected by this progressive increase in distortion.

5.0 CONCLUSIONS

The collapse of the *Buffalo 286* barge in Galveston Bay appears to be attributable to design features and operational procedures which do not allow adequate margins for uncertainties in loading and structural resistance to that loading. The MAESTRO analysis shows that, in ideal circumstances, the structure had a strength 4 to 8 percent greater than required by the load at the time of failure. A number of factors may have reduced the resistance of the structure such that this failure was possible.

- The use of angle stiffeners. The use of such unsymmetrical stiffeners, because of their uncertain compressive strength behavior, could conceivably be a contributing factor, but are most likely not the prime cause of premature failure.
- The use of serrated/intermittently welded stiffeners. The currently unknown effects of the use of serrated stiffeners (and their large unsupported spans of plating) on the collapse strength at this time appears to be the primary contender in explaining the apparent premature failure. Based on the U.S. Navy's experience with a similar structural configuration, it is conceivable that this construction technique may have reduced the strength of the barge on the order of 15-20%. If such a reduction occurred, this could have lowered the strength of the barge well beyond the point where failure would occur. This is a subject which clearly needs closer study.
- Failure by progressive damage. The age of the barge allows the possibility of progressive damage mechanisms playing a role in the weakening of the structure. The U.S. Navy is currently investigating this phenomenon.

6.0 RECOMMENDATIONS

Future work concerning oil bunker barge structural design should focus on the effects of the serrated stiffeners using detailed numerical (finite element) analysis and possibly model tests. Revised operational guidelines to reduce the loading would allow a greater safety margin without need for structural modifications on the existing fleet.

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APPENDIX: ON PLATE BUCKLING AS THE FAILURE MECHANISM IN THE ULTIMATE COLLAPSE OF AN OIL BUNKER BARGE.

Introduction

The structural configuration of the barge uses construction techniques not necessarily considered in the ultimate strength theories currently used for longitudinally stiffened panels under axial compression. The theories of stiffened panel ultimate strength are predicated on the ideas proposed by Von Karmen which require the formation of an edge stress. Ultimate strength is considered the point beyond which the load-carrying capacity is diminished. The theory for ultimate strength of stiffened panels assumes a failure progression where the unstiffened plating between stiffeners gradually loses its effectiveness under compressive loading, shedding the load to the stiffener and the associated plate flange. This idealized component approximates the behavior of a column and is modeled as such. The width of the plate flange is called the effective breadth, and is some calculated fraction of the stiffener spacing. This theory assumes the use of continuous welds being used to attach the stiffener to the plate. When this is not the case, the path to an analytical, closed form solution to the stiffened panel strength is suspect. The additional presence of serrations in the stiffeners on the oil bunker barge under investigation causes an unsupported, 9-inch span to exist in the plate flange in the longitudinal direction. If local buckling occurs in this region, the plate's behavior as the plate flange of the combined section becomes unclear. The plate flange is an important contributor to the overall strength of the stiffener/plate column, and should it become ineffective, the column will not be able to take the loads as is intended in the theory.

Samples were taken of the plating in the deck and bottom of the barge and then tested for yield strength. Of the nine samples, the minimum yield strength was 40.3 ksi and the maximum was 50.4 ksi. The distribution was roughly uniform and slightly skewed to the lower end, leading to no firm conclusion as to the distribution of the population from which the plating material was drawn. The minimum value should be used for future calculations to be conservative. The lower 95% confidence bound for the mean of the sample population is 41.7 ksi, quite close to the minimum sample value, and certainly within one standard deviation. As this value is quite a bit above the 32 ksi yield strength used in the ULTSTR and MAESTRO analyses, the strength prediction based on the measured data minimum value would be expected to show a greater margin of safety. This phenomena led the authors to hypothesize that another failure mechanism, not as dependent upon yield strength, is dominating the ultimate strength.

Failure Theory

Simple, idealized calculations for elastic buckling may give some guidance on the possible causes of overall hull-girder collapse and are presented below. These are by no means definitive, but may shed some light on the plate behavior not considered in the numerical analyses conducted using ULTSTR and MAESTRO.

Using Bryan's equation (discussed in Hughes, 1988) for elastic buckling of unstiffened plate, one may arrive at a predicted strength of 18.6 ksi for the unstiffened plating between the stiffeners. This formulation is independent of yield strength, and is a function of the elastic modulus(E), thickness(t), stiffener spacing or plate width (b), and a scale factor k. k is considered to be 4 as is appropriate for a "long" plate, where the aspect ratio is 3.88.

$$\sigma_E = \frac{k\pi^2 E}{12(1-\nu)^2}\left(\frac{t}{b}\right)^2$$

For the plating in the deck of the barge between the stiffeners, the values are: $t = 5/16$ in, $b = 25$ in, $E = 30\text{x}10^6$ psi, $\nu = 0.3$ (Poisson's ratio), and $k = 4$. This gives an elastic buckling stress of 18.6 ksi, not accounting for the edge restraints. If the presence of the intermittent welds is considered to add an inch to the apparent width of the plating, the elastic stress drops to 16 ksi, and to 12.9 ksi should one add 5 inches. This sensitivity to width would suggest that the lack of attachment of the stiffener to the plating could significantly reduce the plating's ability to carry primary inplane compressive loading in the deck of the barge.

If the response of the plating between welds is evaluated, the theory which may be applied is Euler buckling (Hughes, 1988). Bryan's equation as used above, was adapted from Euler's to account for edge restraint. Euler's equation is:

$$\sigma_{CR} = \frac{\pi^2 EI}{L^2 A}.$$

The unsupported longitudinal gap (span) between welds of 9 inches would seem to have an unknown quantity of fixity at the sides, yet magnitudes less fixity than assumed for Bryan's formulation. The repeating distance of the weld center is 12 inches, and may be assumed to create a node in the deflection wave pattern, should the plating between welds in the serration distort due to plate buckling. This node would be the effective bound on the longitudinal span of the plating, and could be viewed as approximating simply supported end fixity. Therefore the length, L, could be taken as approximately 12 in. If the equation is applied per unit width, the area, A, reduces to t, and the moment of inertia, I, reduces to $t^3/12$. Inputting these values into the Euler buckling equation predicts the onset of elastic buckling to occur at 16.7 ksi. This calculation assumes flat plating, so it may not be conservative. Thus at load levels above that corresponding to deck stresses of 16.7 ksi, the effectiveness of the plate flange in the 9-inch intervals where the stiffener is not attached to the plating, effectively disappears, and the ability of the stiffener alone to carry additional load is simply inadequate.

Conclusion

The strength predicted above seems to approximate the stress levels seen at the time of hull girder collapse of the barge, and may be the fundamental cause. If the plating, and stiffener/plate columns become ineffective due to elastic buckling under roughly the same stress levels, the load would be shed to the hard-corners formed at the longitudinal bulkhead/deck intersection and the intersection of the sides and the deck. These discrete points would not be strong enough to prevent complete collapse of the section. If plate buckling of the sort hypothesized above is occurring, the strength of these barges may be considerably less than shown by ULTSTR. The presence of intermittent welds alone, without the serrations, may also lead to a similar result, but possibly not as drastic.

Recommendations

A literature search and review of previous work on strength issues stemming from intermittant welds and serrated stiffeners is recommended. A numerical analysis of the behavior of the stiffened panels with serrated stiffeners, may allow a better understanding of the physical behavior to be developed. With this knowledge a test program may be designed to test the theory using scaled models of the deck panels. The results should be studied to develop analytical tools for use by the designer when intermittent welds are deemed necessary.